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Work in Progress: Creation and Implementation of a Customized, AI-assisted Bio-Inspired Mind Mapping Method for Enhanced Ideation in Engineering Design

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Abstract

This work details a customized, Artificial Intelligence (AI) assisted method and digital tool to create bio-inspired mind maps for enhancing ideation in the engineering design process. Using biological examples as inspiration for innovation in the design ideation process, sometimes referred to as biomimicry, is well-documented and has been prolific. One problem with implementing biomimetic approaches is that knowledge of the vast biological realm can be elusive for engineering teams. Often, an engineering design team does not have specific knowledge of diverse biological domains such as cellular biology, animal biology, and plant biology. Therefore, finding the "best", or even relevant, biological examples to inspire ideation for a specific design problem is challenging. As a result, the common approach of seeking biological analogies from within a designer's experience often produces limited results. In addition, while simple use of a web search engine may expand the set of analogies, both the relevance of the results to the exact design problem and the organization of the analogies (simple web search output) can be improved. AI can assist in finding appropriate biological analogies across these different biological domains by leveraging large language models trained on extensive text corpora encompassing biological, scientific, and engineering content. Our work introduces a custom AI-driven process to generate biological examples to populate the mind maps. Specifically, we wrote software that interacts with the AI, which we coded to use specific descriptions of the design problem (functions) to produce a set of relevant biological analogies displayed in mind map format. Mind maps are a proven method for structuring and organizing design ideation. Mind maps visually show the relationships between different ideas by having the main design challenge in the center of the mind map and then identifying categories and subcategories of potential solutions. Functional decomposition of a design problem is used as the input to the AI-assisted method, where the functions define the hierarchical categories and subcategories of the mind map. This approach ensures that the AI-generated biological analogies are directly tailored to the specific design challenge. The initial assessment indicates that the AI-assisted method appears to be effective and is well received by the designers. Overall, this work demonstrates that integrating AI-assisted biological analogy generation into mind maps, using input from functional decomposition, can enhance bio-inspired ideation in engineering design.

1. Background and literature review

1.1 Background on AI

In recent years, Artificial Intelligence (AI) has rapidly become integrated into many facets of life. Advances have led to increasingly powerful and effective AI tools resulting in expanded use cases for the technology. Though AI's rise to ubiquity is relatively recent, the concept of AI originated in the 1950s from English computer scientist Alan Turing and the "Turing Test" [1]. The exact term "Artificial Intelligence" only emerged later when Professor John McCarthy coined the term during the 1956 Dartmouth Summer Research Project on Artificial Intelligence [2]. AI is a general term for technology that "enables computers and machines to simulate human learning, comprehension, problem solving, decision making, creativity and autonomy" [3]. Under the general umbrella of AI are multiple AI-based technologies that can assist in the engineering design process.

Generative AI is a category of AI that centers around having models create specifically tuned work [4]. Yuan Sun et al. describe generative AI as "designed to generate novel content, insights, and solutions by identifying, replicating, and recomposing intricate patterns within existing data" [5]. In order to create relevant output, models are trained on broad, diverse datasets. Thus, these AI tools are sometimes called Large Language Models (LLM). Elements of randomness are integrated within the model to enable unique outputs and greater diversity of thinking for the same prompt [4, 6, 7]. The diversity of sources and inherent randomness of generative AI may allow it to have enhanced creativity in responses compared to humans [8]. Generative AI's have been made to create content in multiple forms, from text to imagery to audio. Generative AI is one of the most widely used forms of AI, with popular chatbots such as OpenAI's ChatGPT and Anthropic's Claude being both widely used examples of the technology in action [9, 10].

AI has been found to be helpful across various engineering design methods, though efficacy varies depending on the combination of design methods and the AI tools used [11]. AI may be particularly helpful in the earlier stages of design, such as ideation (concept generation). In particular, AI tools can make connections that humans often cannot. This plays directly into our work to use AI to create biological analogies in the ideation stage of design. Allison et al. describe how "Human cognitive limits constrain such design processes, creating an opportunity for AI models to accelerate the ability of engineering to better meet the needs of humanity" [12].

Additionally, different metrics are needed to evaluate the AI's performance due to the distinctly different goals for regular AI tools and AI tools tailored explicitly for engineering design. Regenwetter et al. propose a set of design-specific metrics to evaluate deep generative models in engineering design, addressing the limitations of traditional metrics like likelihood and visual similarity. Metrics of particular importance are constraint satisfaction, functional performance, novelty, and conditioning, which are critical for engineering applications [13].

1.2 Background on function-based design-by-analogy and mind maps

The current work employs a design method called functional decomposition, which describes what the specific design needs to accomplish. This ***functional description is used as input to our custom AI tool, which then generates biological analogies in mind map form***. Below, we provide some background on both functional decomposition and mind maps as context for our work.

Functional decomposition, or functional descriptions, are widely recognized as a successful method for generating innovative solutions [14]. To maximize the effectiveness of functional descriptions, design problems should be expressed using solution-neutral functions. Specifically, the neutral functions describe what must be achieved without constraining how it is achieved [15, 16]. This abstraction limits the tendency to fixate on familiar solutions within engineering design and encourages the exploration of a wider range of concepts.

One method of representing solution-neutral functions is by using a functional basis, as introduced by Hirtz [25]. Pahl and Beitz [17] describe the method for organizing this information. Specifically, this system organizes all possible functions into flows of material, energy, and signal, with all functions being further derived from these three core concepts (e.g. the function “raise liquid” is simply a more nuanced form of “move material”). To ensure consistent communication of function and flow relationships, the functional basis uses verb–object pairs (such as “move material”) as its standard descriptive form [17]. Otto and Wood built on Pahl and Beitz’s work by developing a “black box model”, which describes a system being designed using its functional inputs and outputs [16, 18]. This model allowed larger functions to be broken down into smaller subfunctions, which are more specific actions that a system must perform to turn its inputs into its outputs [16]. Breaking down a function into its subfunctions reduces the complexity of the engineering task being performed, allowing for more productive and efficient ideation [16]. Both functions and subfunctions are used as input to our AI tool. Our custom code then instructs the AI to generate mind maps of biological analogies that are relevant to the functions.

Design-by-analogy (DbA) is the technique of transferring knowledge from a source domain to a target domain via a mapping between their functional representations [14, 18]. One particularly effective form of DbA is bio-inspired design, in which analogical transfer is performed between biological source systems and technical target problems [19]. In this process, abstracted biological principles, often extracted from organism-level functions or ecological interactions, are mapped onto engineering contexts through a function-focused representation [19]. This approach benefits from the diversity and optimization in biological systems, which have evolved to solve complex physical, chemical, and organizational challenges. As a result, bio-inspired design can yield innovative solutions that would be unlikely to emerge from purely within-domain ideation [20].

Others have worked to implement the use of AI to enhance DbA. Jian et al state that DbA is "a design methodology wherein new solutions, opportunities or designs are generated in a target domain based on inspiration drawn from a source domain; it can benefit designers in mitigating design fixation and improving design ideation outcomes"[22]. Song et al point out that the breadth of the analogical search is critical and, of course, this can be potentially enhanced using AI [23]. Muller et al specifically use generative AI to enhance analogy-based ideation [24].

One method of engaging bio-inspired design is the utilization of mind maps. Mind maps are tools that organize concepts in a radial, branching structure, starting from a central idea or theme and expanding outward into subtopics and related ideas [20,21]. This format supports associative thinking by making relationships between concepts explicit and visually accessible. In the context of bio-inspired design, mind maps can integrate biological functions, engineering requirements, and abstract principles in a single visual framework, helping designers traverse from near-field analogies to far-field inspirations more systematically [20].

2. Research question

Research question: Can an AI tool that uses functional decomposition as input and creates bioinspired analogies presented in mind map form, enhance ideation in the engineering design process.

In our research question, the terms "functional decomposition" imply that the design functions of the specific design challenge will be used as input for the custom AI tool that generates the mind map. The user provides an initial verb-noun function, and the AI mind map tool performs hierarchical functional decomposition. We define "enhance ideation" as an increase in the quantity, and perhaps also the novelty of produced ideas. In this "work in progess", our initial assessment relies on measuring the quantity of ideas that an ideation technique produces as the primary numerical assessment metric. Novelty is assessed only in a preliminary fashion through qualitative feedback from the designers.

3. AI mind map tool development and example

To develop an AI mind map tool suitable for ideation we used OpenAI's GPTs tool, which allows one to create a customizable version of ChatGPT tailored to a specific purpose with unique instructions, knowledge, and functions. This is done by overlaying our own coded instructions as an instruction protocol for the GPT. Through a series of revisions, we developed a set of instructions for the GPT with specific requirements for the content, organization, and format of the mind map. Given the limitations of the GPT-4o model (OpenAI's flagship model at the time of developing the tool) in producing large visual mind maps with substantial nuanced data, we divided the mind map development process into two parts. First, content is generated in the form of a hierarchical outline (see figure 3 as an example), and second, the outline is then converted into a visual mind map (see figures 4 & 5 as an example). This is done through a downloadable link that takes the user to an external location (not the GPT).

To effectively organize the generated outline, we required functional decomposition with hierarchical verb-noun functions [21] in our instructions for the GPT. As a result, the outline creates a large solution-neutral design space that encourages innovative ideas. This tiered system takes an initial verb-noun function as input and breaks it down into more specific verb-noun functions that fit in the category of the initial input function. The newly generated "child" functions are then broken down to generate even more specific related verb-noun "grandchild" functions, and those functions are again broken down such that three levels of functional decomposition are achieved. Therefore, the tool is designed in such a way that the user can choose what level of functional specificity to start at by inputting the first verb-noun function from which the outline is generated. After the three levels of functional breakdown, two biological analogies are generated by the GPT for each of the most specific verb-noun functions at the last level of the mind map outline. The GPT is instructed to generate the most relevant and high-performing biological examples for each verb-noun function, based on its learned representations from biological and engineering literature. In addition to the biological entities themselves, the GPT generates three brief statements for each entity describing 1) what it is, 2) how it works, and 3) why it's useful for engineering design. This entire outline generation process is initiated automatically once the user inputs the initial verb-noun function in the custom GPT prompt bar we created as part of the GUI for our tool.

Since the GPT-4o model can deprioritize strict instruction-following in favor of shorter responses, a "primer" prompt was included for the user to click on before providing their function input. This method of prompt engineering ensured that a much more accurate and thorough outline was generated, rather than the GPT ignoring certain instructions in favor of a quicker response. This can be seen in Figure 1.

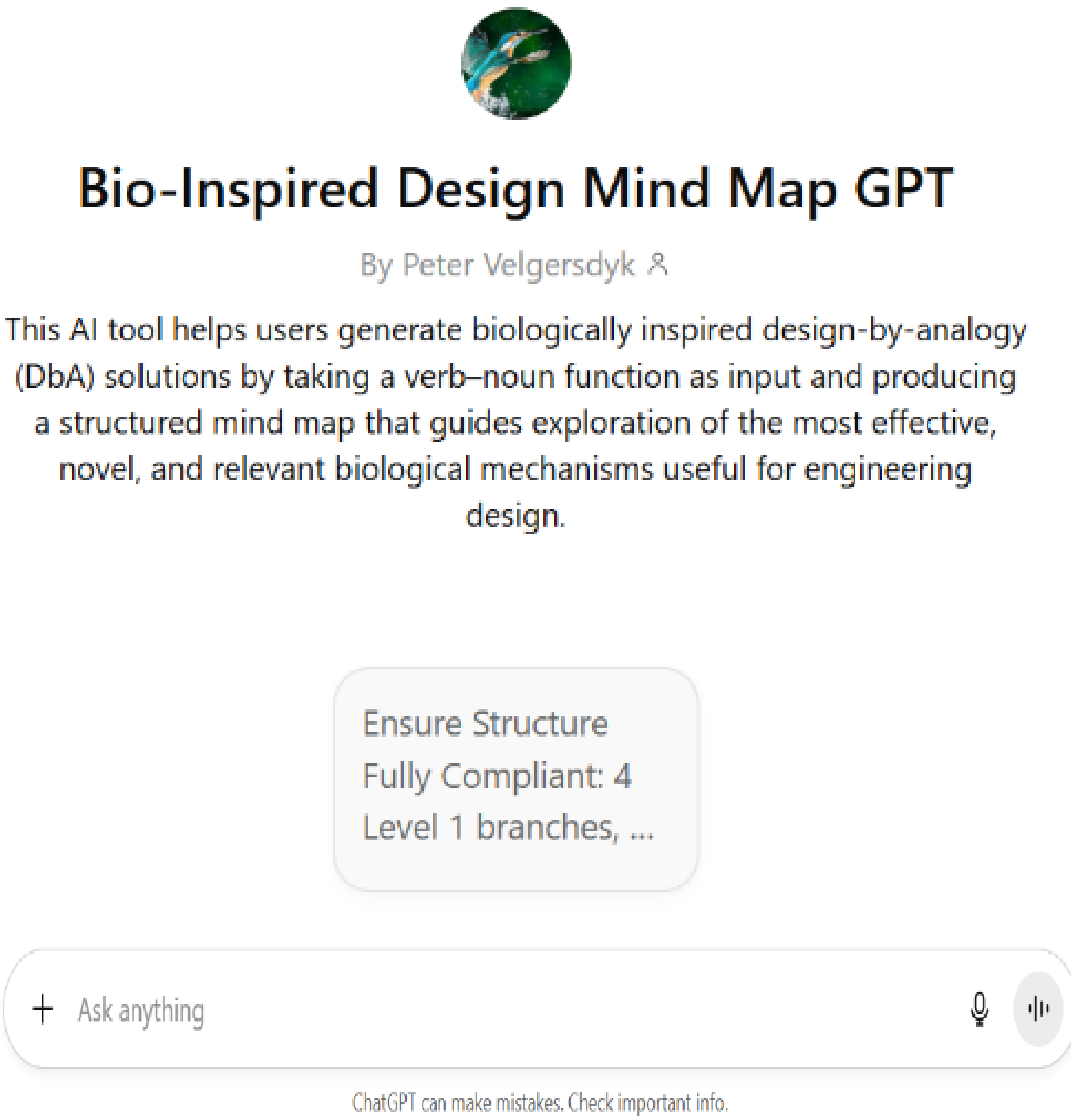

Figure 1 – Initial GUI for the Custom GPT Input

Once the user provides this initial input for this GPT tool, the primer prompt is suggested on the GPT details and description page. This page is shown in Figure 2.

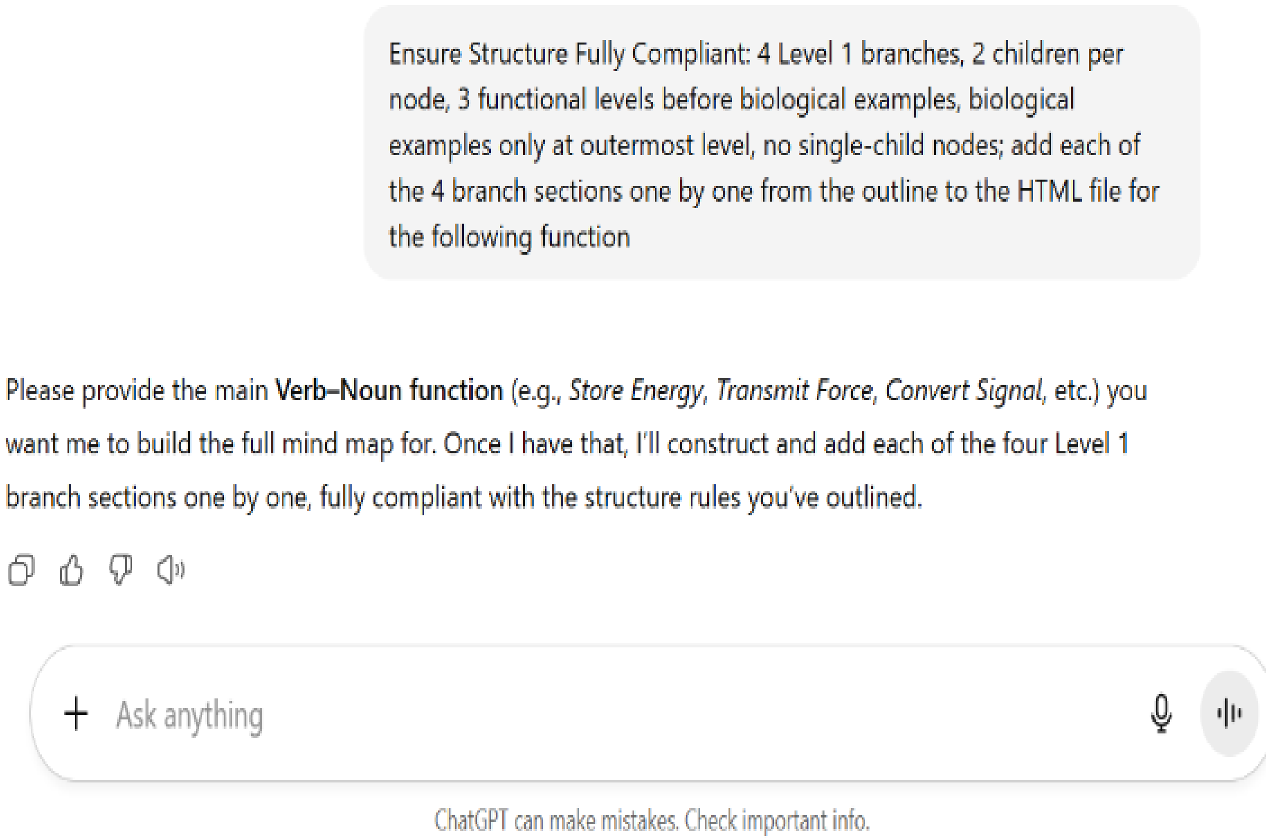

Figure 2 – Subsequent Input for Custom

After clicking on the primer prompt, the user can then input the verb-noun function they would like to use for ideating design solutions. Figure 3 partially displays the prompt bar input and generated outline for the initial input function "reduce slipping" using this GPT tool. Additional outlines for the functions "improve gripping", "adjust posture" and "adapt to surface" complete the GPT output. Each of these three has a similar set of details displayed below the primary function. For this example, the function "reduce slipping" is intended to help the user develop ideas for how to design a safe shower.

reduce slipping

Thanks! Let's begin the mind map construction for the function **Reduce Slipping**.

Central Function: Reduce Slipping

1.1 Increase Friction

- **1.1.1 Modify Surface Texture**
  - **1.1.1.1 Add Microstructures**
    - **Gecko Footpads**
      - *What it Does:* Increases contact grip on smooth vertical surfaces
      - *How it Works:* Millions of microscopic setae generate van der Waals forces with surfaces
      - *Why it's Effective:* Offers dry adhesion and high reusability across diverse surfaces
    - **Tree Frog Toe Pads**
      - *What it Does:* Enhances grip on wet leaves and smooth surfaces
      - *How it Works:* Hexagonal epithelial cells with mucus film create capillary and friction forces
      - *Why it's Effective:* Maintains adhesion in humid environments with minimal energy use
  - **1.1.1.2 Increase Roughness**
    - **Cat Tongue Papillae**
      - *What it Does:* Improves grip during grooming and handling prey
      - *How it Works:* Backward-facing keratin spines penetrate and latch onto surfaces
      - *Why it's Effective:* Enhances material engagement with minimal surface damage
    - **Goat Hooves**
      - *What it Does:* Enhances traction on rocky mountain terrain
      - *How it Works:* Split hooves deform to interlock with uneven surfaces
      - *Why it's Effective:* Maximizes friction on unstable or inclined ground
- **1.1.2 Alter Surface Chemistry**
  - **1.1.2.1 Secrete Adhesives**
    - **Slug Mucus**
      - *What it Does:* Temporarily increases surface stickiness
      - *How it Works:* Slime forms a viscoelastic gel that binds substrate irregularities
      - *Why it's Effective:* Energy-efficient, temporary adhesion that adapts to surface contours
    - **Mussel Foot Proteins**
      - *What it Does:* Adheres to wet and turbulent surfaces
      - *How it Works:* Specialized proteins form covalent bonds even in saltwater
      - *Why it's Effective:* Maintains strong grip under harsh, variable conditions
  - **1.1.2.2 Generate Electrostatic Forces**
    - **Spider Silk Threads**
      - *What it Does:* Attracts charged particles and surfaces
      - *How it Works:* Silk threads hold static charges, enhancing stickiness
      - *Why it's Effective:* Lightweight, passive adhesion mechanism for diverse surfaces
    - **Beetle Feet**
      - *What it Does:* Maintains contact grip through surface charging
      - *How it Works:* Footpad microstructures generate electrostatic forces on contact
      - *Why it's Effective:* Enables climbing without chemical adhesives

Figure 3 – Partial Output from the Custom GPT Based on the Function of "Reduce Slipping"

Once the outline is generated, the GPT then converts it to a downloadable HTML file containing a visual mind map using Mind Elixir, an open-source mind map-making software. This is achieved via the GPT instructions that package the outline into a hierarchical JSON file format that is compatible with Mind Elixir's source code. A download link for the mind map is then created. Figure 4 displays the visual mind map that was produced for the function "Reduce Slipping". Although the details in figure 4 are too small to read, the complete mind map is shown to illustrate the dozens of potential bio-inspired solutions that are provided. The red boxed portion of the mind map is expanded for readability and shown in Figure 5.

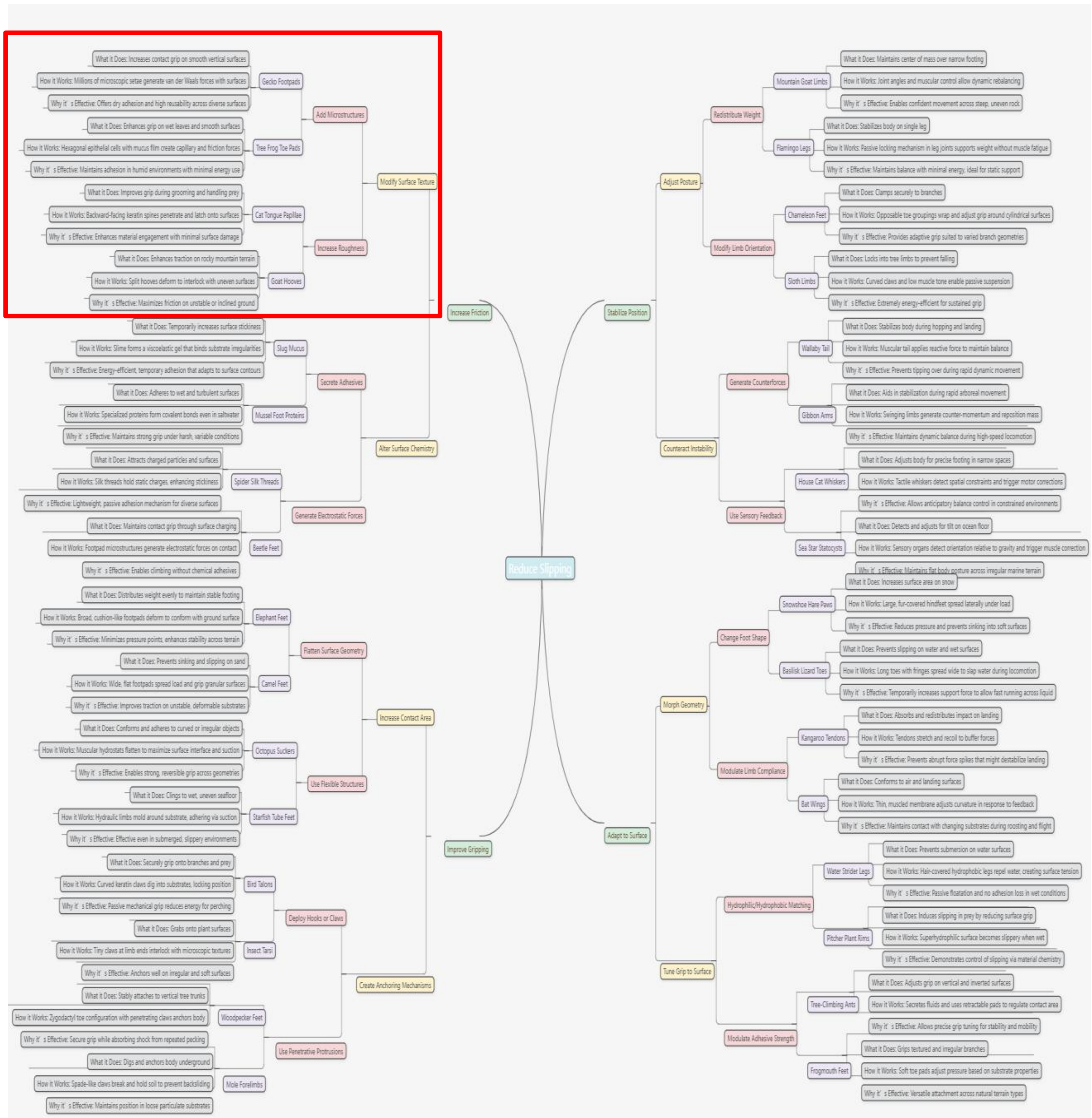

Figure 4 – Mind Map Output for key function "Reduce Slipping"

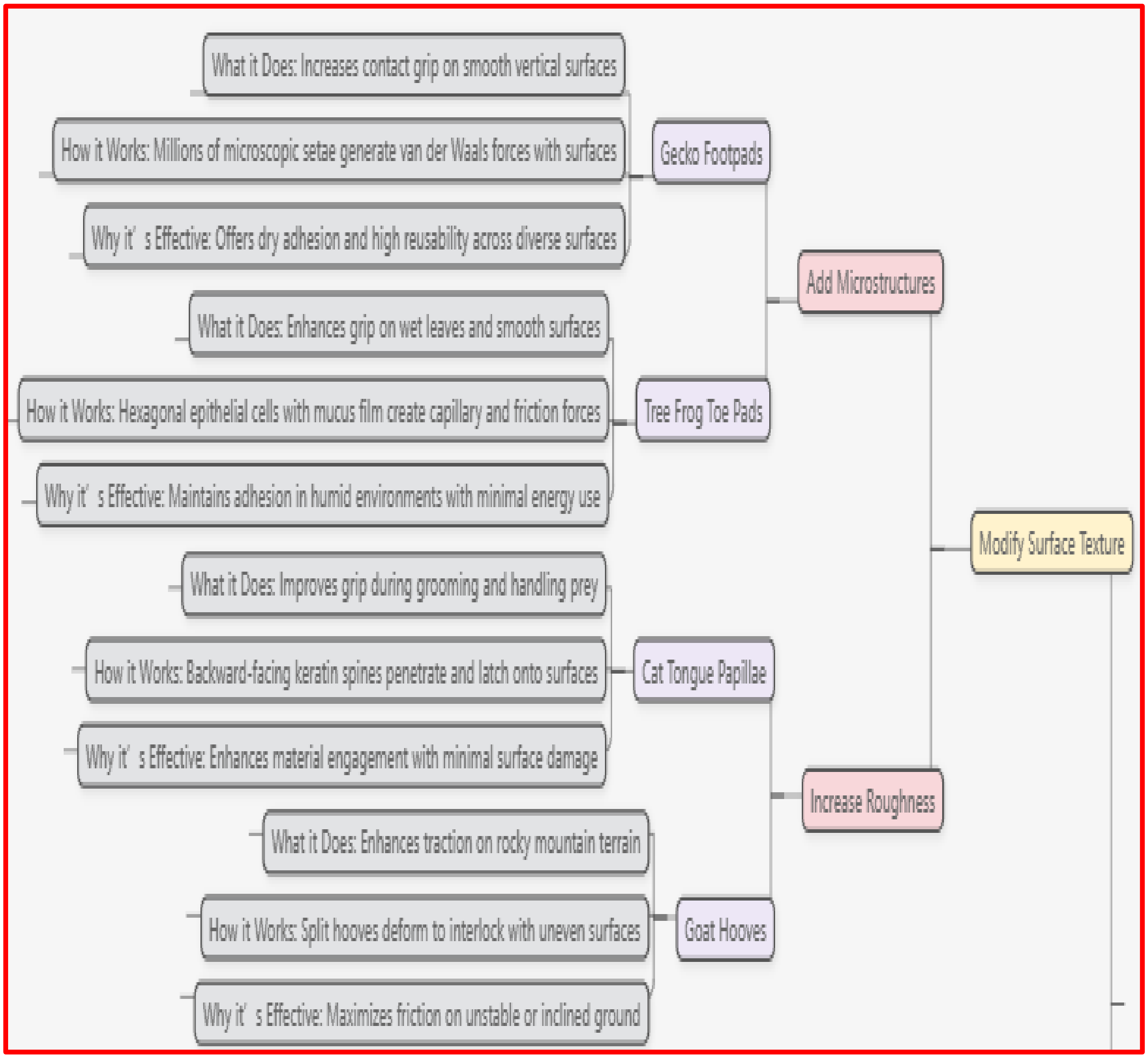

Figure 5 – Upper Left (Expanded) Portion of Mind Map

The user experience of the tool therefore, consists of accessing the custom GPT online via OpenAI, clicking the primer prompt, inputting a verb-noun function, and then clicking the generated mind map file. This process from start to finish takes approximately 1-2 minutes. Additionally, we found that after generating the first mind map, the GPT tool can repeat the process for new input functions in the same chat session even more efficiently.

4. Initial Assessment

At the time of this "work in progress" publication, we have only begun the assessment of the bio-inspired mind mapping design tool. We do, however, have some initial qualitative and quantitative data. We tested our tool through an experiment where two groups of five engineering designers per group were given the same design problem and were given the same amount of time to ideate (30 minutes). While both groups were encouraged to include biological analogies as inspiration in their ideation, one group used our AI mind mapping tool and the other group did not. The quantitative data indicate that, when our AI-assisted mind mapping tool is used, the number of viable ideas increases significantly compared to when the tool is not used. This is based on a comparison of the average number of ideas generated by each group. The group using the mind mapping tool produced 37 ideas and the group not using the tool produced 14 ideas, resulting in a mean-comparison p-value of <0.05. This, of course, is for a single design problem and with only two groups of engineering designers, making the results admittedly preliminary.

In our future work, we will work on a more in-depth assessment. Comparison of the ideation capability of each group, use of the tool by different groups of engineering designers, level of sophistication of the ideas produced, and usability of the AI tool will all be investigated. In addition, initial data suggests that the novelty of the solution set increases for the group that employed the AI tool. This is based, so far, only on qualitative feedback from the designers themselves.

Numerous other engineering designers have used the mind mapping tool, in an ad hoc fashion, and have provided additional qualitative feedback. Overall, the responses were positive, with reactions indicating that the tool enhanced their ability to implement bio-inspired ideation. These users also gave specific suggestions for refinement of the tool. One example was to add some additional details to the biological analogies to provide a clearer picture of how that biological system's function might apply to the design of the product. We are working to implement those ideas.

5. Conclusions, Future Work and Acknowledgements

An AI-assisted tool has been produced that can create mind maps of bio-inspired ideas for use in engineering design. The tool uses an AI GPT core from OpenAI that we have customized to produce the mind maps. The tool uses the design problem's functional description as input. The process for creating the mind maps is easy, often taking only a few minutes to produce dozens of relevant bio-inspired ideas. Initial assessment results indicate an overall benefit from the custom AI-assisted tool that creates bio-inspired main maps. Specifically, the number of ideas produced through the use of the tool was greater than when the tool was not available. Other measures of effectiveness, including those related to usability of the tool, were positive.

Our tool is not the only way that can assist engineers in the development of bio-inspired ideas. Other methods, such as websites like AskNature.org are commonly used. In the future, our tool will be evaluated in comparison to this and other methods for creating bio-inspired ideas. In addition, other quantitative and non-quantitative assessments will be obtained, including suggestions from engineering designers on how to improve the tool. Finally, the tool should be evaluated by additional engineers to broaden the assessment foundation.

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